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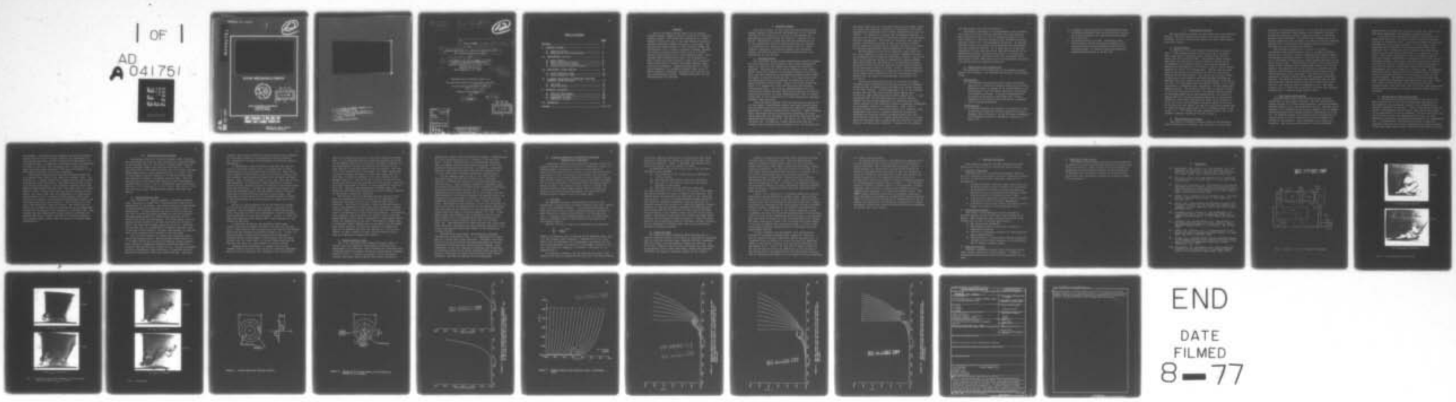

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SCHOOL OF MECHANICAL ENGINEERING
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6 COHERENT STRUCTURE OF A TURBULENT BOUNDARY LAYER IN A CONVECTED REFERENCE FRAME.

by


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# TABLE OF CONTENTS

## ABSTRACT

This is an interim annual report for an ongoing research program studying coherent structure in turbulent boundary layers. The design and development of a water channel facility for use in flow visualization studies of coherent turbulent boundary structure is described. The particularly unique aspects of this facility include the incorporation of 1) a moving reference (viewing) platform for study of relative motion effects and 2) a closed circuit television monitoring and recording system. Preliminary flow visualization results are presented for both a fixed and moving reference frame, and a tentative vortex-loop model of coherent turbulent boundary layer structure is proposed. Computer simulations of a transverse structure in a turbulent boundary layer are presented showing a remarkable similarity with experimental flow visualization results. Research directions for the following year are outlined.

# I. RESEARCH SUMMARY

This first section of this report briefly summarizes the present status of the research and highlights of our findings. Included in this section is a listing of publications and presentations resulting from the research. Sections II, III, and IV, respectively, provide more detailed descriptions of 1) the experimental facility developed during this research, 2) preliminary flow visualization results, and 3) a simple computer simulation of turbulent boundary flow structure. Section V briefly outlines our research directions for the second year of this program.

## A. Research Review

The first year of the present experimental research program has been completed, and although we have encountered some delays, all facets of the research are either on or ahead of schedule. Construction of the moving reference frame system, which allows the "tracking" of convected boundary layer structure, has been completed and preliminary evaluations have shown the system to function extremely well. The video viewing and recording system has been purchased and integrated into the moving reference frame system. Tests of the video system have shown it to perform well both for monitoring and recording visualization data. The existing hydrogen bubble-wire flow visualization system has been improved and refined, and several unique probe designs have been developed which allow us greater versatility in our visualizations of three-dimensional turbulent boundary layer structure.

Using the above systems, which are described in section II of this report, visualization results have been obtained which are consistent with previous studies and indicate a remarkable coherency of turbulent boundary layer structure. Fixed reference frame visualizations have revealed both transverse and axial structures within the boundary layer which are identical to those identified by Runstadler et al. [1], Kim et al. [2], and Offen and Kline [3]. In addition, strong similarities with the boundary layer structure work of Nychas et al. [4] and Falco [5] have been noted (this is a bit more difficult since these latter two works used different visualization techniques, which makes comparison of visualized flow structure characteristics more indirect). As indicated in Section III (Preliminary Results), a tentative vortex loop model of turbulent boundary layer structure has been hypothesized. This model is consistent with both our initial visualization results as well as the work of others. We are presently pursuing several studies (see Section V) which are directed specifically toward examination of this model.

The development of the moving reference frame system for the water channel now allows us to "chase" turbulent structure as it develops and is convected downstream. However, the use of this moving reference system introduced some unique problems. The first problem was the need for a non-interferring bubble-wire probe which would allow vertical and horizontal profiles to be visualized at small $y^+$ values ($y^+<20$). This problem was solved by the development of a probe with the bubble producing wires shapes like an inverted T and the wire supports well removed from the region of visualization (see Section II.C and III.A).

The second problem was the lack of a method for proper interpretation of bubble-wire flow visualizations of turbulent structure when the bubble probe and camera are moving relative to the mean velocity. It was recognized early in the research program that the same flow structure would appear quite differently when visualized using a moving bubble-wire. It was recognized that not only would there be relative velocity effects, but the visual appearance of a structure would be a strong function of the structure's location (upstream, downstream, or coincident) relative to a bubble wire. Thus, using a simplistic model of a convected structure in an otherwise time-independent flow field, a computer simulation program was developed [9] which can produce simulated bubble-wire flow visualization pictures of a simple convected vortex in a 1/7th power law velocity field, illustrating the effects of relative velocity and bubble wire location. A summary of this program and some results are shown in Section IV.

Preliminary comparison of the experimental flow visualization results with the computer simulation has been dramatic. The indication is that at least a significant portion of the outer region of a turbulent boundary layer contains convected, decaying vortices of a distinguishable character. An improved simulation model is presently being developed and implemented into the simulation program. It is hoped that this improved simulation will not only provide an improved simulation of our experimental results, but will also allow us to iteratively extract quantitative information about the visualized structure using a direct video overlay of our experimental visualization results with the computer simulation.

B. Publications and Presentations

The completion of the first year of the present research program has resulted in the following publications and presentations:

Publications

1. "Preliminary Flow Visualization Studies of Coherent Structure in a Turbulent Boundary Layer Using a Moving Reference Frame," to appear as an invited paper in the Proceedings of the 14th Annual Meeting of the Society of Engineering Science. A parallel presentation of the material contained in this paper will also be presented at the Annual meeting of SES on 15 November 1977 at Lehigh University.

Presentations

1. A research presentation entitled, "A Preview of a Flow Visualization System for Study of Coherent Turbulent Boundary Layer Structure," at the 4th Annual Midwestern Fluid Mechanics Retreat in Rochester, Indiana on 22 April 1977.

2. A research seminar entitled, "An Experimental Study of Coherent Boundary Layer Structure Using a Moving T.V. Viewing System," at NASA-Ames Research Center on 26 May 1977.
3. An invited seminar entitled, "Preliminary Flow Visualization Studies of Turbulent Boundary Layer Structure Using a Moving Reference Frame and T.V. Viewing System," at Stanford University Mechanical Engineering Department on 26 May 1977.

## II. EXPERIMENTAL FACILITY

The experimental facility can be divided into four different systems: the water channel flow system, the moving reference platform, the flow visualization system, and the closed circuit television system.

### A. Water Channel

A schematic of the water channel flow system is shown in Fig. 1. The working section of this system is a 5.2 meters long, open surface Plexiglass water channel with a bed 0.9 meters wide by 0.30 meters deep. For boundary layer studies, flat plate test sections of up to 4 meters in length can be accomodated in the working section. The maximum volumetric flowrate for the channel is 1.25 $m^3$/min. with an overall system capacity of 4.20 $m^3$ of filtered water. Special care has been taken in the design and fabrication of the inlet and outlet sections of the test channel. The inlet flow initially enters a large inlet tank through a specially designed distribution manifold and a 5 cm thick plastic settling sponge. From the inlet tank, the flow passes into the channel through a 2.5:1 inlet contraction, a honeycomb flow straightener, and two turbulence damping screens. The resulting inlet flow is uniform to within $\pm$ 0.5% across the entire channel. The channel outlet employs an accordian-shaped screen pack approximately 3 cm thick as a damping device to prevent upstream propagation of surface disturbances. With false side walls in place, inlet velocities of up to 30 cm/s are attainable with water depths of 10 cm to 25 cm above the test plate. By use of an auxiliary heating unit to raise the water temperature to 35 C, Reynolds numbers of up to $Re_L \cong 1.2 \times 10^6$ (based on plate length) and $Re_\theta \cong 2.6 \times 10^3$ (based on momentum thickness) can be attained.

### B. Moving Reference Platform

The effect of a moving reference frame on the detection and visualization of turbulent flow structure is given close attention in the present research. It is felt that the ability to vary the reference frame velocity is a necessity in determining the velocity, character, and time history of traveling boundary layer structure. To provide the necessary moving reference system for this research, an axially traversing reference platform with a continuously adjustable traverse velocity was developed for use with the water channel.

The reference platform is a 1.0 meter x 0.6 meter rectangular frame constructed of 5 cm x 5 cm square aluminum tubing with a series of interior stainless steel support shafts for equipment and probe support. The platform rides on a pair of 3.8 cm diameter hardened steel shafts mounted directly to the water channel frame. The platform is guided on one shaft by two linear motion bearings which provide both vertical and lateral support; the opposite side of the platform is supported on two precision ball bearing cam followers which have only rolling contact with the top of the shaft. The drive motor is a one horsepower variable speed DC motor with reversing and dynamic braking. The speed is variable from essentially zero to 2800 rpm, with motor speed accuracy within 2% regardless of variations in line current, ambient temperature, etc. The motor coupled to a 3.7 meter long lead screw, can drive the reference platform over a velocity range from 0-21 cm/s.

### C. Flow Visualization System

Hydrogen bubble wire flow visualization was employed exclusively in the present research. The flow visualization system consists of: a power pulse generator, specially designed hydrogen bubble wires, and illumination source. The power pulse generator is a specially built DC power supply which can supply controlled square-wave voltage pulses at frequencies up to 225 Hz. The hydrogen bubble wire probes utilize strategically located 0.05 mm to 0.02 mm platinum wires as the cathode in a process of electrolysis. When connected to the power pulse generator, the platinum wires generate very fine hydrogen bubbles which are swept off the wire, forming time lines in the flow which approximate instantaneous velocity profiles.

In previous flow visualization studies, only single wire probes have been used, yielding velocity profiles in either a vertical or horizontal plane. A new type of probe that has been developed for the present research is a T-wire probe. This probe employs a horizontal wire stretched across the probe supports, with a second wire spot-welded to the middle of the horizontal wire and running vertically to an upper arm of the probe. This probe configuration forms an inverted T bubble-wire which allows simultaneous visualization of the flow in two orthogonal planes. This probe works particularly well both 1) for views of vertical velocity profiles (since the horizontal wire can lie flush on a horizontal surface with negligible disturbance) and 2) for views at an oblique angle. In addition, this probe can be moved relative to a boundary while allowing vertical velocity profiles to be visualized to within 0.5 mm of the boundary. The bubbles from the bubble-wire probes are made visible by illuminating the bubble-wires from above (about a 35° angle to the vertical) using a conventional slide projector with a 500 watt bulb. Due to the low light sensitivity of the television camera, no higher intensity light source is required.

### D. Closed Circuit Television System

It was recognized early in the research that one of the major limitations in most flow visualization experiments is the inability to have instant access to the visual data for immediate playback and analysis. Film is both expensive and requires a development delay of several days before the results of an experimental run can be observed. And more often than not, one finds that either the camera position, focus, or light setting was incorrect, necessitating refilming of an experimental run. A closed-circuit television system with a video tape recorder eliminates all of the uncertainties of camera position, focus, and light setting since a scene is viewed just as it will be recorded. One limitation of television is that the maximum framing rate is fixed at 60 pps, however, the resolution of a high quality television picture is essentially equivalent to a 16 mm movie film. In addition, television pictures can generally be taken in very poor light conditions and a 1 hour reel of video tape costs about the same as 100 feet of developed 16 mm film (about 4 minutes worth) and is reusable!

The present closed-circuit television system consists of a TV camera, lens, monitor, and video tape recorder (VTR). The TV camera is a compact surveillance camera with 625 line resolution and low light sensitivity. The camera (with lens) is compact enough to be mounted on the reference platform either from above or cantilevered from the side. The camera lens is a remote control, 14 mm - 140 mm zoom lens with various close-up attachments. The zoom, focus, and iris adjustments are remotely controlled from a unit in a central control console (which also houses the TV monitor, the reference platform speed control, and the bubble wire power pulse control). The TV monitor is a 625 line, high-resolution, nine-inch monitor. The output from the camera can be viewed on-line with the monitor and simultaneously recorded on the system's final component, a time-lapse VTR. This recorder has the capability of taping events in real-time and playing them back in either real-time or at several different time delayed speeds ranging from 1/9 real-time to single frame (stop-action).

## III. PRELIMINARY VISUAL RESULTS

Preliminary studies of turbulent boundary layer structure have been conducted with the flow visualization system described in the previous section. Both fixed reference frame tests and moving reference frame tests have been performed on a 2.45 m flat plate with a free stream velocity ($U_\infty$) of 10 cm/s. The Reynolds number based on plate length was $Re_L \cong 2.5 \times 10^5$, thus a 2.5 mm diameter trip rod located 2.5 cm from the leading edge was required to produce a turbulent boundary layer. Near the trailing edge of the plate (the location of the visualization pictures shown in Fig. 2 and 3), the boundary layer characteristics were $\delta \cong 7.25$ cm, $Re_\delta \cong 7.4 \times 10^3$, $Re_\theta \cong 700$, and $u_\tau \cong 0.45$ cm/s ($Re_\theta$ and $u_\tau$ were estimated from standard empirical relations).

### A. Fixed Reference Frame

Fig. 2 shows two typical examples of turbulent boundary layer structure as viewed from a fixed reference frame and recorded using the TV system. Both these pictures are photographs of single-frame stills displayed on the TV monitor (from recorded data). In both pictures the flow is left to right and the view is across the plate and normal to the flow direction. The approximate location of $y^+=200$ above the plate is indicated to the right of each picture. The T-wire probe, with the horizontal wire located 0.5 mm from the surface of the plate ($y^+\cong 2$), was used with a bubble pulse rate of 40 Hz. Note that the vertical wire is located where the bubble time lines begin on the left of each picture; the dark lower boundary in each picture is the location of the surface of the flat plate.

Fig. 2a is an example of a large scale structure moving within the boundary layer. This structure extends upward to a $y^+$ of about 200 and has a distinct transverse vortical appearance, similar to comparable turbulent structures observed in previous flow visualization studies [2,3,5]. During an extended period of observation, many structures of transverse vortical appearance were seen to pass the viewing position. The size, position, and angular velocity of these structures were observed to vary widely, however, it appeared that these structures were essentially the same flow phenomenon in different states of development.

A longitudinal vortex structure, which has also been observed in previous studies [2,3], is a second type of large scale boundary layer structure that was observed. These structures appeared to have their origin near the plate surface, with the structure itself projecting upward from the plate and downstream. Such a structure is shown in Fig. 2b. Note that for all cases observed, the diameter of vortex appeared to increase and the angular velocity appeared to decrease as the vortex moved away from the surface. As with the transverse structures, the size, the outermost extent, and the angular velocity of these longitudinal structures were observed to vary widely. The longitudinal vortex shown in Fig. 2b extends outward to $y^+ \cong 150$; it was not uncommon for these structures to extend out as far as $y^+ = 200$.

In Fig. 2, the horizontal wire of the T-wire is located at the base of the vertical wire, normal to the plane of the pictures. This horizontal wire generates closely spaced time lines (initially at $y^+ \cong 2$) which approximate a sheet of bubbles, thus visualizing the flow near the plate. In Fig. 2, these time lines are observed as the intense white region adjacent to the surface of the plate.

In both Fig. 2a and 2b, the horizontal bubble sheet clearly shows fluid "bulges" and fluid lift-ups from near the plate. These smaller flow structures are the lift-ups and "bursts" which have been observed in previous studies [2,3]. In Fig. 2a and 2b several of these flow structures can be observed in different stages of development, from "bulges" near the plate surface (Fig. 2b, lower left) to "bursts" penetrating well out into the flow (Fig. 2a, lower center to right at $y^+ \cong 100$).

Although still speculative, it appears from the preliminary results that the large scale flow structures described above are not two different flow phenomena, but are different parts of an ejected ring vortex in the final stages of development. It is speculated that the transverse vortical structure is the leading edge of the loop vortex (clockwise rotation) and the longitudinal vortices are trailing side portions of the loop (similar to trailing vortices from an airfoil). The location of the trailing end of the vortex ring (which should have a counter clockwise rotation) is still under study, but it is felt that it should be embedded in the lower portion of the boundary layer ($y^+ < 50$) and is not as easily identifiable due to the very large velocity gradients near the surface. Note that this speculated model is similar to that proposed by Offen and Kline [8]. However, they hypothesize a somewhat open loop structure with indefinite terminations near the surface, instead of the present closed loop structure.

The "bursts" which are observed near the surface of the plate are speculated to be the result of an interaction of fluid near the plate surface with a previous loop vortex structure. The "burst" so formed is also speculated to play a role in the formation of other loop vortex structures; whether a "burst" forms a loop vortex directly or has a more indirect role in its formation is still under investigation. It should be noted, however, that what appear as "bursts" near a wall have been observed to have either a transverse or longitudinal orientation (or combination of the two), which makes it appear that a visualized "burst" depends both on the location of the bubble wire and on the plane in which the structure is visualized. Thus, it is possible that what one observes as a lift-up and "burst" is only a "piece" of newly initiated vortex loop as seen in a particular visualization plane.

B. Moving Reference Frame

Fig. 3 is a series of four selected pictures (from a 4 second video tape sequence) illustrating a portion of the development of a transverse vortex structure as visualized with a hydrogen bubble wire probe and the TV camera moving at approximately 0.78 $U_\infty$. It should be pointed out that the single, vertical wire probe used to obtain these shots introduced a moving probe support with an equivalent diameter of approximately $d^+=7$ into the boundary layer at a location $y^+\cong 20$ above the plate. However, repeated tests and observations indicated that the support had little noticeable influence on the flow structure characteristics observed. In addition, essentially identical structures have been observed just recently using a T-wire probe (which introduces negligible interference).

For the sequence shown in Fig. 3, the outer extent of the vortex moves from $y^+\cong 120$ to $y^+\cong 190$ over a convected distance of $x^+\cong 1400$ and travels at an average convected velocity of 0.89 $U_\infty$. This convection velocity is consistent with the convection velocities of large scale structure as determined in previous experimental studies [4,6,7]. Two remarkable characteristics of these pictures are 1) the cohrent, well defined boundary of the vortex throughout the sequence and 2) the similarity of the structure in the Fig. 3d with the previous transverse structure shown in Fig. 2a for a fixed reference frame. With regard to the *coherency*, it is to be noted that the core of the vortex is generally free of any bubbles, indicating that the origin of the vortex has to be from the bubble-free region below the level of the probe support ($y^+ \lesssim 25$). In the actual video tape sequence, this is observed to be the case. With regard to size, the growth of the vortex within the sequence shown is from a diameter $d^+\cong 30$ (Fig. 3a) to $d^+\cong 90$ (Fig. 3d). The implications of these pictures that large scale outer structures originate from wall generated ejections is felt to be a particularly significant aspect of the present preliminary results.

As pointed out previously, the developing transverse structure as illustrated in Fig. 3 is speculated to be only a part of a larger loop vortex structure. Obviously, much more data will be required before the speculated model can be confirmed and further structure characteristics defined. With refinements of the data acquisition technique and utilization of the T-wire probe in the moving reference frame system, more detailed information on large scale structures, wall "burst" structure, and their interaction will be obtainable.

# IV. A SIMPLE SIMULATION OF TRANSVERSE TURBULENT BOUNDARY LAYER STRUCTURE

A phenomenon which has been repeatedly observed in both the present research and work by others is a "transverse vortex", so called because it appears as a vortical motion moving at slightly slower than the free stream, but with its axis of rotation normal to the flow direction and parallel with the wall. This section of this report summarizes a recent computer simulation of this traveling, transverse structure developed by Crosen [9] in a study carried out in parallel with the present experimental research. The purpose of this study was to model the vortical motion (in some simple manner) and to subsequently simulate flow visualization experiments (in both fixed and moving reference frames) using this simple model.

## A. The Model

The physical situation investigated is that of a two-dimensional, incompressible turbulent boundary layer over a smooth wall at zero pressure gradient. It is presumed that there is some mean flow $\bar{U}_\infty$ with a vortex superimposed upon and moving at some fraction of the mean flow velocity. The flow detector (i.e., a velocity probe, hydrogen bubble wire, or other instrument) is assumed to move in the x-direction with position $\bar{P}$ and constant speed v.

The mean flow $\bar{U}_o$ is taken to be described by a power law:

$$\frac{U_o}{U_\infty} = \left(\frac{y}{\delta(x)}\right)^{1/n}$$

where $U_\infty$ is the mean flow at the edge of the boundary layer, and $\delta$ is the boundary layer thickness. Assuming that $\delta$ is a constant (this is reasonable for the distances over which the vortex can be observed), then the mean flow becomes a function only of y, but with no y component of velocity. The power, n, is chosen to be 7.

By kinematic arguments, one can show that the path of the vortex center must be convected along with the local mean velocity

(Of course, dynamic effects such as variations in the vortex diameter or strength can change the normal vortex path, but these are neglected). Thus, in the model the relative velocity at the vortex center is forced to vanish.

In establishing the shape of the vortex, the following constraints were imposed:

(1) The influence of the vortex should be confined to a finite region.

(2) The velocity distribution should be continuous.

(3) The slope of the velocity profile at the vortex boundary should vanish.

(4) Mass and kinetic energy should be conserved.

In order to satisfy (1), (2), and (3), an initial vortex shape and velocity profile as shown in Figure 4 was selected. This initial shape also satisfies the first part of (4), conservation of mass. In order to conserve kinetic energy within the flow field (a reasonable assumption since the vortices are normally observed well outside the viscosity dominated, laminar sublayer), a "vortex distortion" parameter was employed which is selected such that the addition of the vortex to the mean flow introduces no net change in the total flow field kinetic energy. The general configuration of a distorted vortex which satisfies this criteria is shown in Figure 5. Thus, by superposition of the distorted vortex on the power law mean velocity, one can "simulate" a boundary layer type of flow containing convected transverse vortices.

## B. Using the Model

The simulation model described above has been used to produce simulated results of two types of experimental techniques used in turbulent boundary layer research: hot-wire anemometer velocity profile data and hydrogen bubble-wire pictures. In both cases, computer codes have been developed that will accept an appropriate set of input conditions, analyze the resulting flowfield, and output a graphical display of the results.

Figure 6 illustrates two extreme cases obtained using the velocity profile simulation code. The left hand velocity profile is what one would measure with an array of hot wire probes (along the y-axis) when a vortex was not present (simply a power law profile). The velocity profile on the right is that which would be measured when the center of a vortex moving at 0.80 $\bar{U}_\infty$ is coincident with the hot-wire probe array. Additional plots of sequential, simulated velocity profiles illustrating the movement of a vortex past a hot-wire probe array are presented in [9]. In general, the sequential profiles are remarkably similar to actual experimental velocity profiles measured during a turbulent "burst" using an actual hot-wire probe array [10].

Figure 7 is a simulation of a hydrogen bubble-wire picture generated using the bubble-wire computer code. This plot was made using a stationary wire, with the vortex initial location slightly more than a half-diameter upstream of the wire. Bubble generation was continued as the vortex passed the wire and moved several diameters downstream to its location indicated by the x in Figure 7. Each time-line in the figure represents a group of bubbles that were all generated simultaneously, with the time-line to the far right representing the first group to be produced. One notes from the figure that the vortex appears to be "rolling up" these time-lines; indeed, this is exactly what would happen if one were to observe the vortex long enough. In fact, there is a strong similarity between Figure 11 and Figure 2a of the experimental results.

To help interpret the experimental flow visualization results for a moving reference frame, simulation cases were run for several different bubble-wire speeds and positions. A "standard" case was defined to be one for which the speed and center of the vortex coincides with the speed and position of the bubble wire. A result for this case is shown in Figure 8. One can see that by moving the bubble-wire at the velocity of the vortex center, the appearance of the bubble-wire visualization is changed dramatically, with the bubble time-lines appearing as a tight, knotted vortex.

As pointed out previously, the bubble-wire position relative to the vortex has a major effect on the visualization picture obtained. This is illustrated in Figures 9 and 10 which simulate the visualization picture which would be obtained if the bubble-wire was moving at the same velocity as the vortex center but was positioned either just ahead of the vortex (Figure 9) or just behind the vortex (Figure 10). Of particular interest is Figure 10 which is remarkably similar to the experimental results shown in Figure 3. This somewhat dramatic similarity between simulation and experiment strongly indicates that at least a portion of the structure that is observed experimentally is a relatively distinct vortex. That such a simple simulation gives such a remarkable comparison with experiment has prompted us to extend the present simulation model to allow for time varying vortex characteristics, and to examine the possibility of developing a simulation of a three-dimensional vortex loop structure consistent with that described in section III of this report.

## V. RESEARCH DIRECTIONS

The following enumerate research directions for the coming year which will be or already are being pursued.

### A. Facility Improvement

The basic facility is essentially complete, however, specific equipment improvements are still required to improve the flow visualization system. Equipment which will be developed are:

1. An improved,higher intensity light source which can be synchronously pulsed to improve T.V. resolution.
2. An improved T-wire probe of minimal interference and which can be constructed using adhesives rather than by soldering (to expedite repair time).
3. A de-airation system for the water channel to better accomodate the use of hot-film anemometers.
4. A mechanism for creating single transverse vortices either in a fixed or moving reference frame.

### B. Visualization Studies

The range of flow conditions will be extended to Reynolds numbers of $Re_L \cong 1.2 \times 10^6$ and a plate length of 3.7 meters. Both extensive fixed and moving reference frame studies will be done to examine specifically:

1) The vortex loop hypothesis.
2) The feedback effect of wall layer "bursts" on transverse structure.
3) The role of transverse structure in initiating wall layer instabilities.
4) The interaction of artificially created transverse vortices with a) fully turbulent, b) transitional, and c) laminar boundary layers.

### C. Anemometer Studies

Hot-wire anemometer studies will be initiated in the water channel system using X-film probes. Attempts at simultaneous bubble-wire and hot-film measurements will be made.

D. Simulation Model Studies

The simple, fixed position transverse vortex model will be modified to allow for both time variation of position and decay of vorticity. Model validity will be evaluated via comparison with experimental results, and the feasibility of developing an interactive correlation of the computer simulations with experimental results via computer graphics will be explored.

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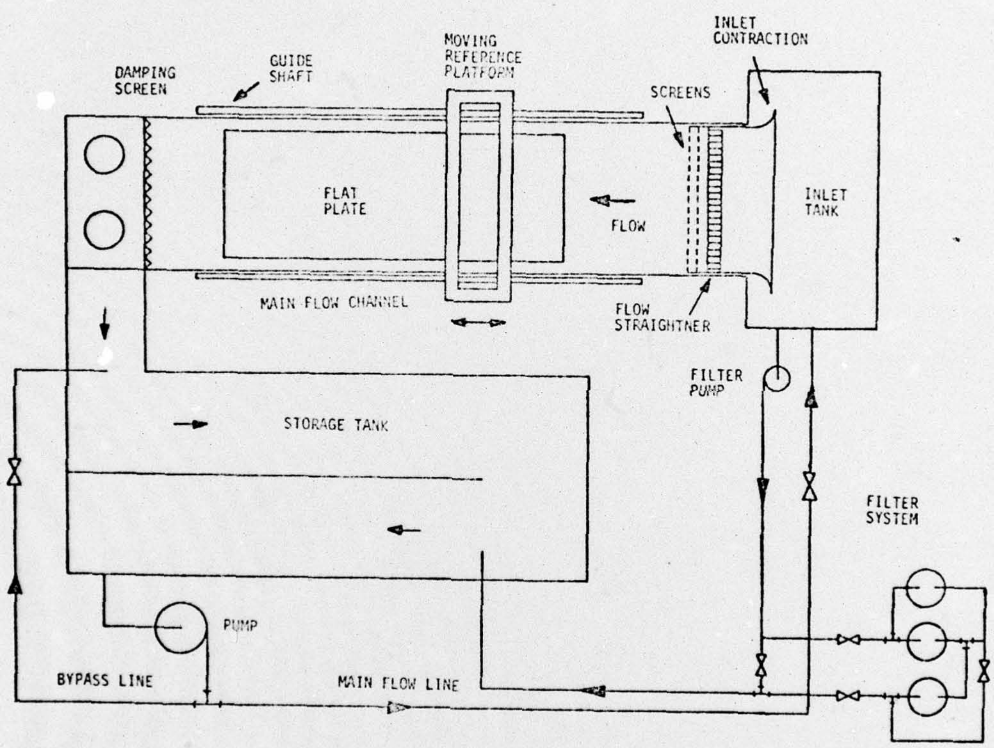
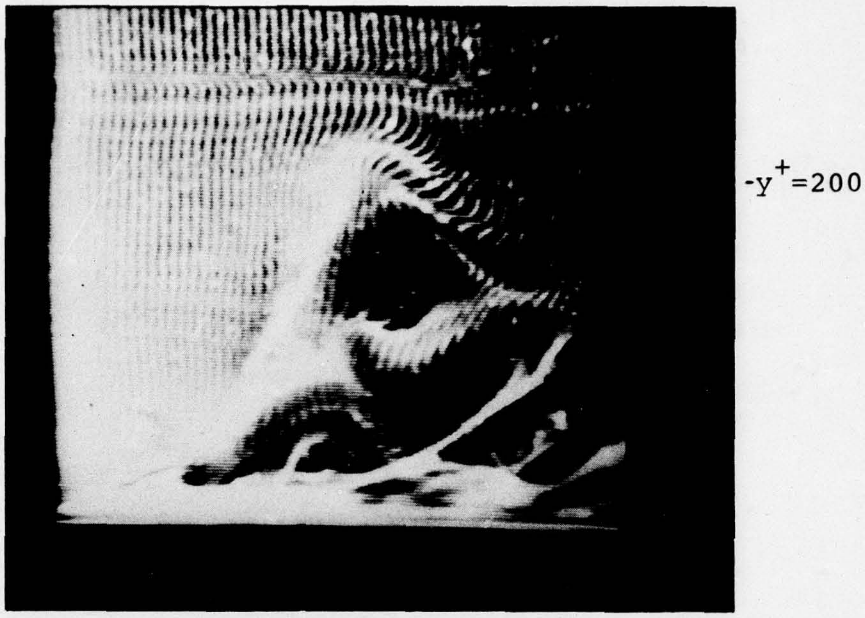
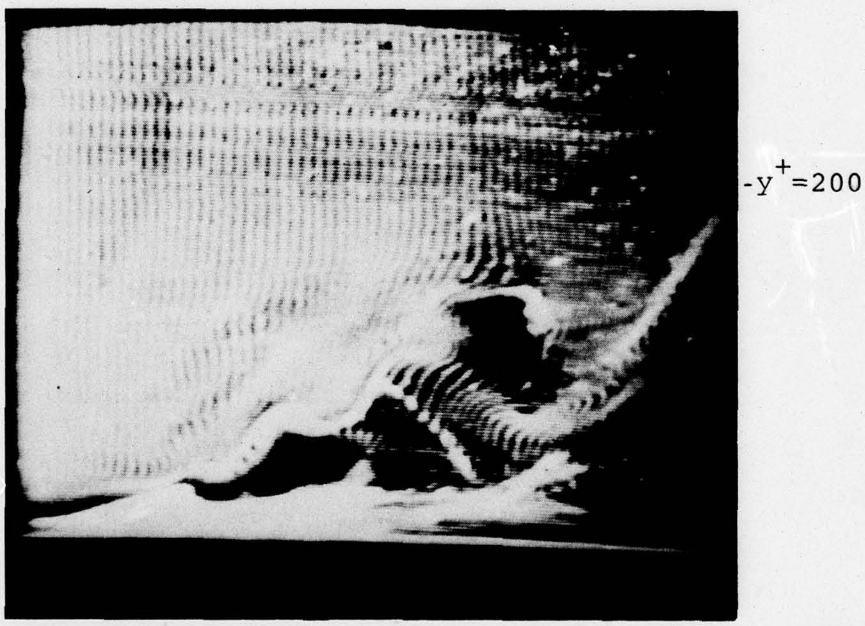



Fig. 1 Schematic of Water Channel Flow System.

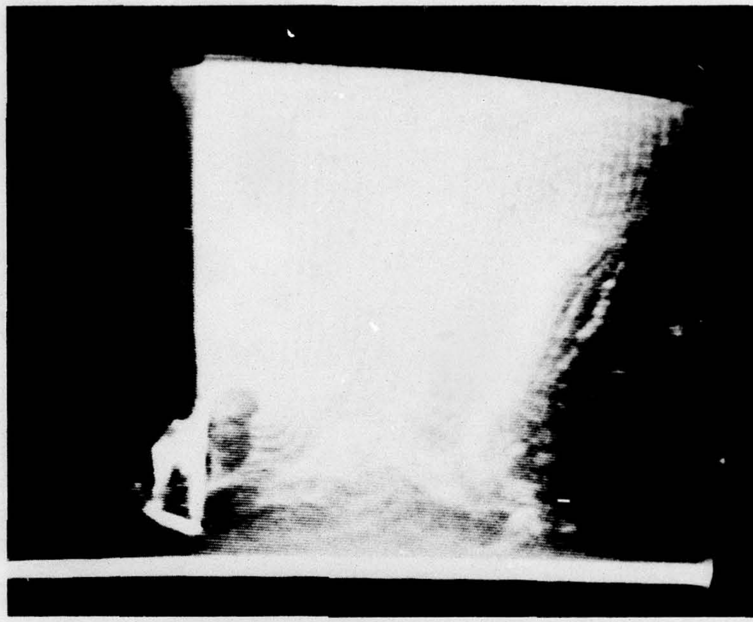



(a) Transverse Structure

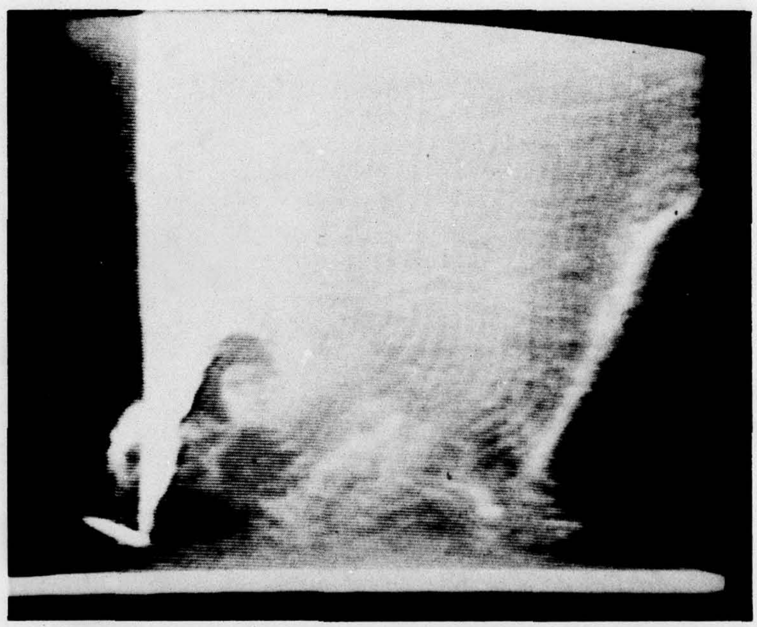



(b) Longitudinal Structure

Fig. 2 Fixed Reference Frame Views.

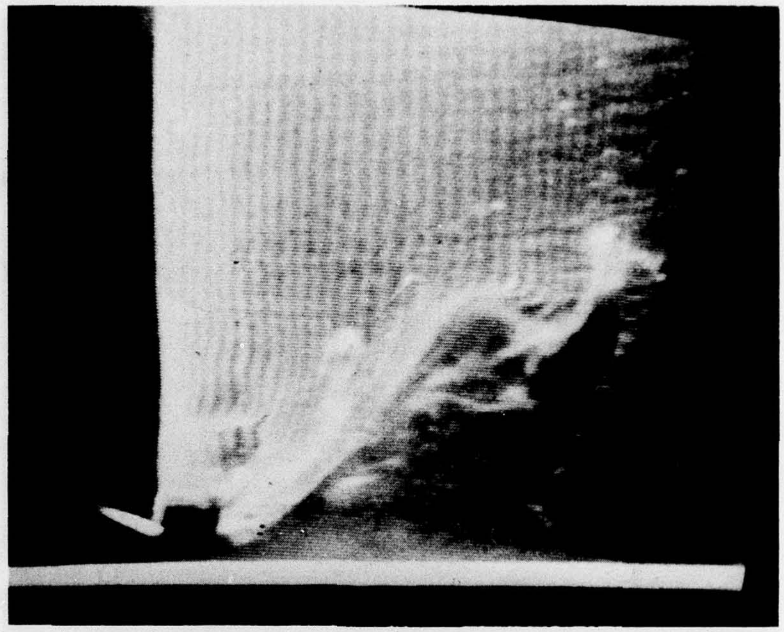



(a) $t_{ref}$ = 0 sec

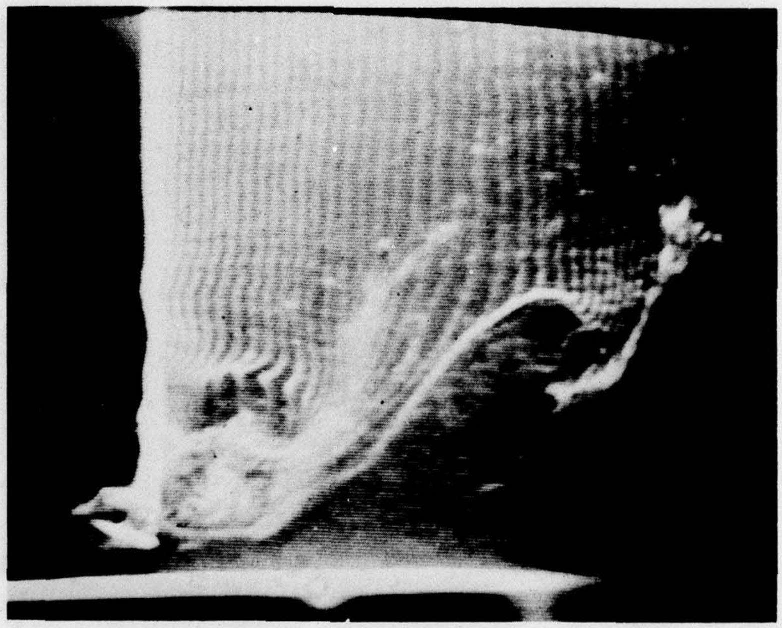



(b) $t_{ref}$ = 0.73 sec

Fig. 3 Transverse vortex development with observation platform moving at $V_{ref}$ = 0.78 $U_\infty$.




(c) $t_{ref}$ = 2.92 sec




(d) $t_{ref}$ = 4.00 sec

Fig. 3 (continued)

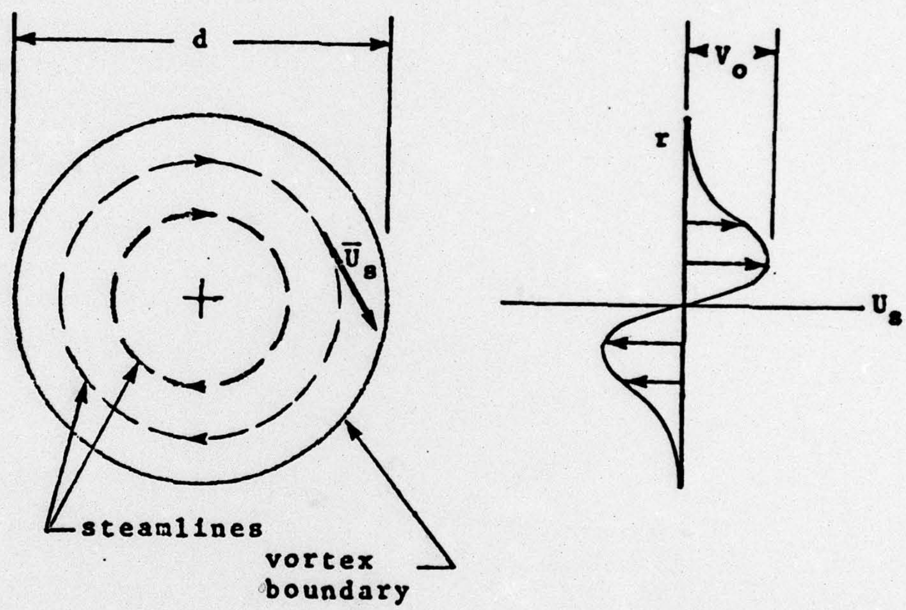



Figure 4. Vortex shape and velocity profile.

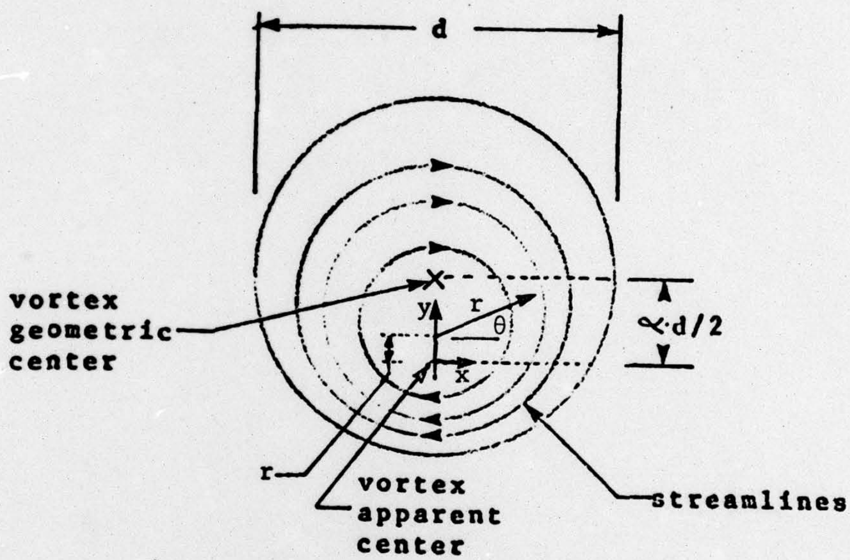



Figure 5. Sketch of the vortex shape if the distortion parameter is included.

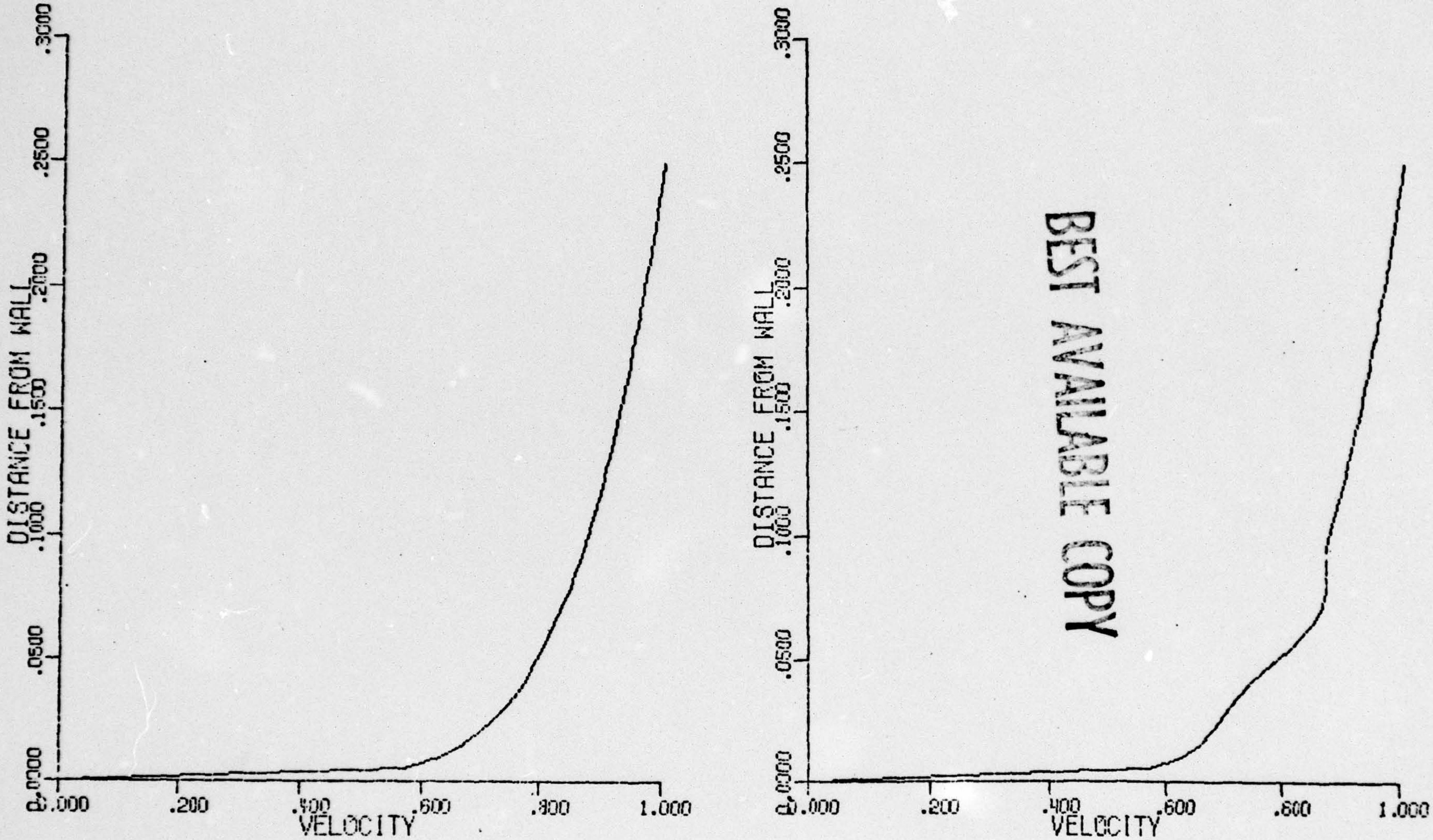





**Figure 6.** Examples of computer generated velocity profiles. On the left is the mean flow (no vortex present), and on the right is the mean flow plus vortex.

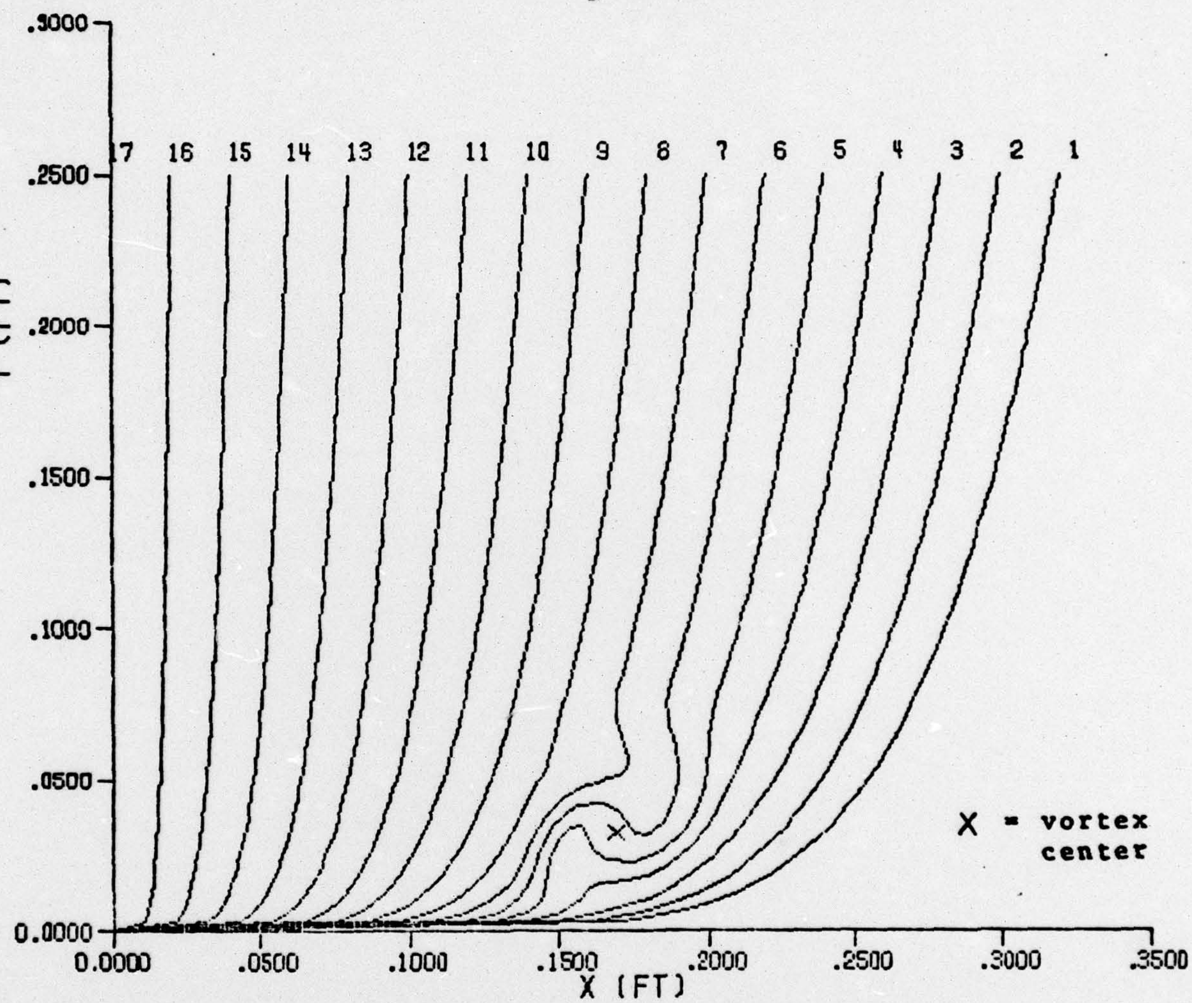



Figure 7. Example bubble wire simulation with a stationary wire.

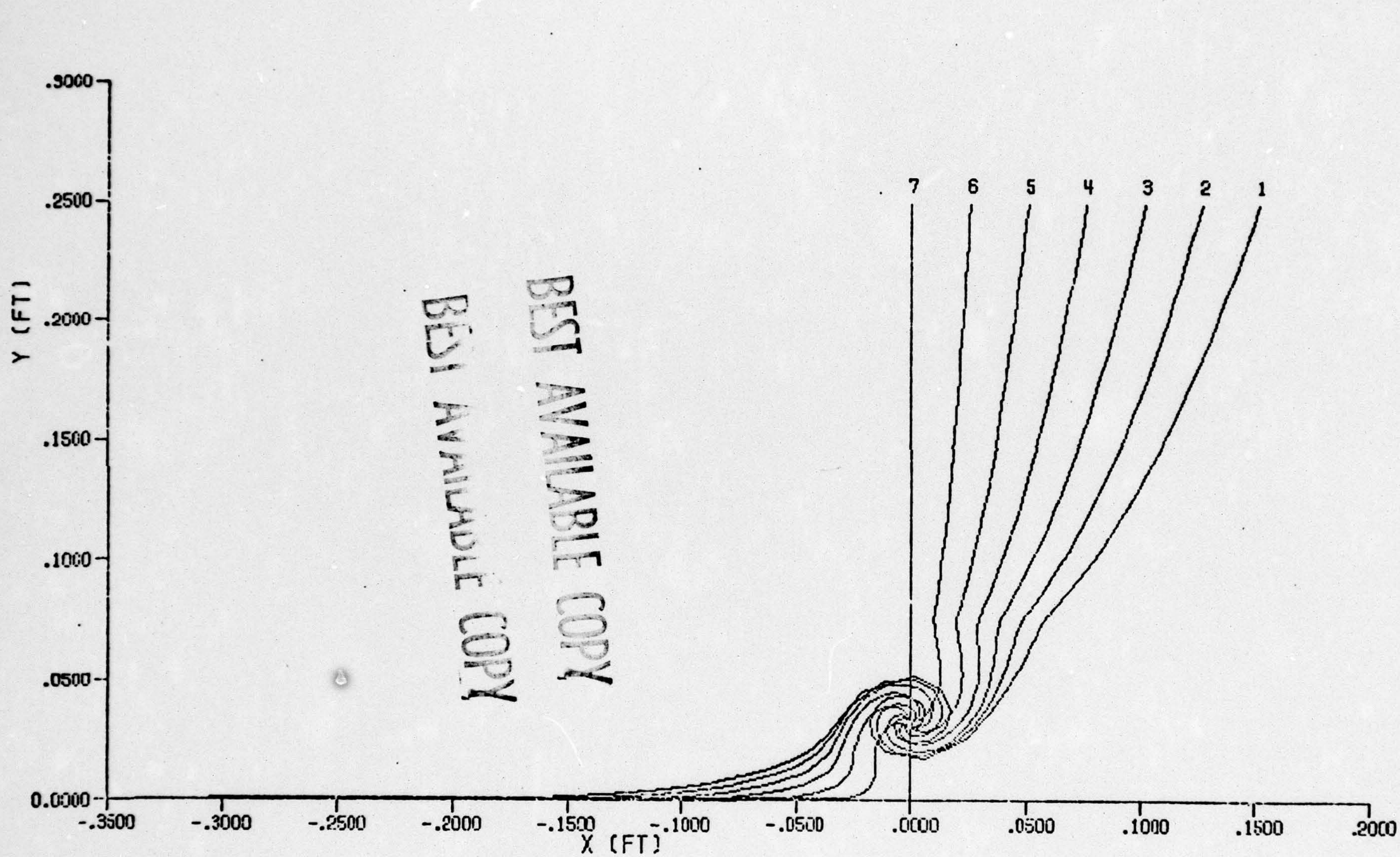





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Figure 8. Hydrogen bubble wire simulation with wire moving at same speed and location as vortex. The numbers above the figure represent the order in which the lines were generated.

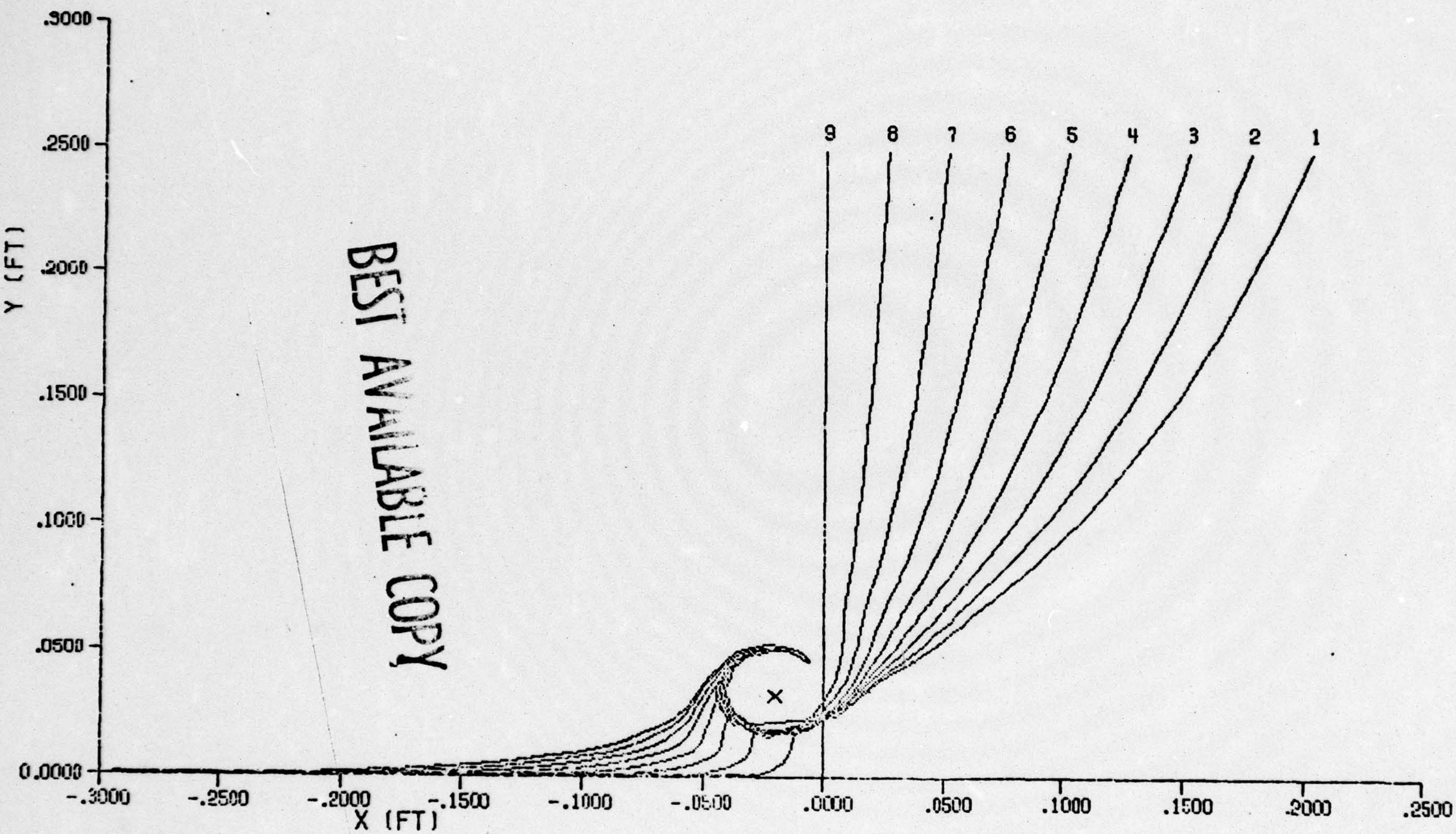




Figure 9. Hydroben bubble wire simulation with wire moving at same speed as vortex but with the vortex center behind the wire.

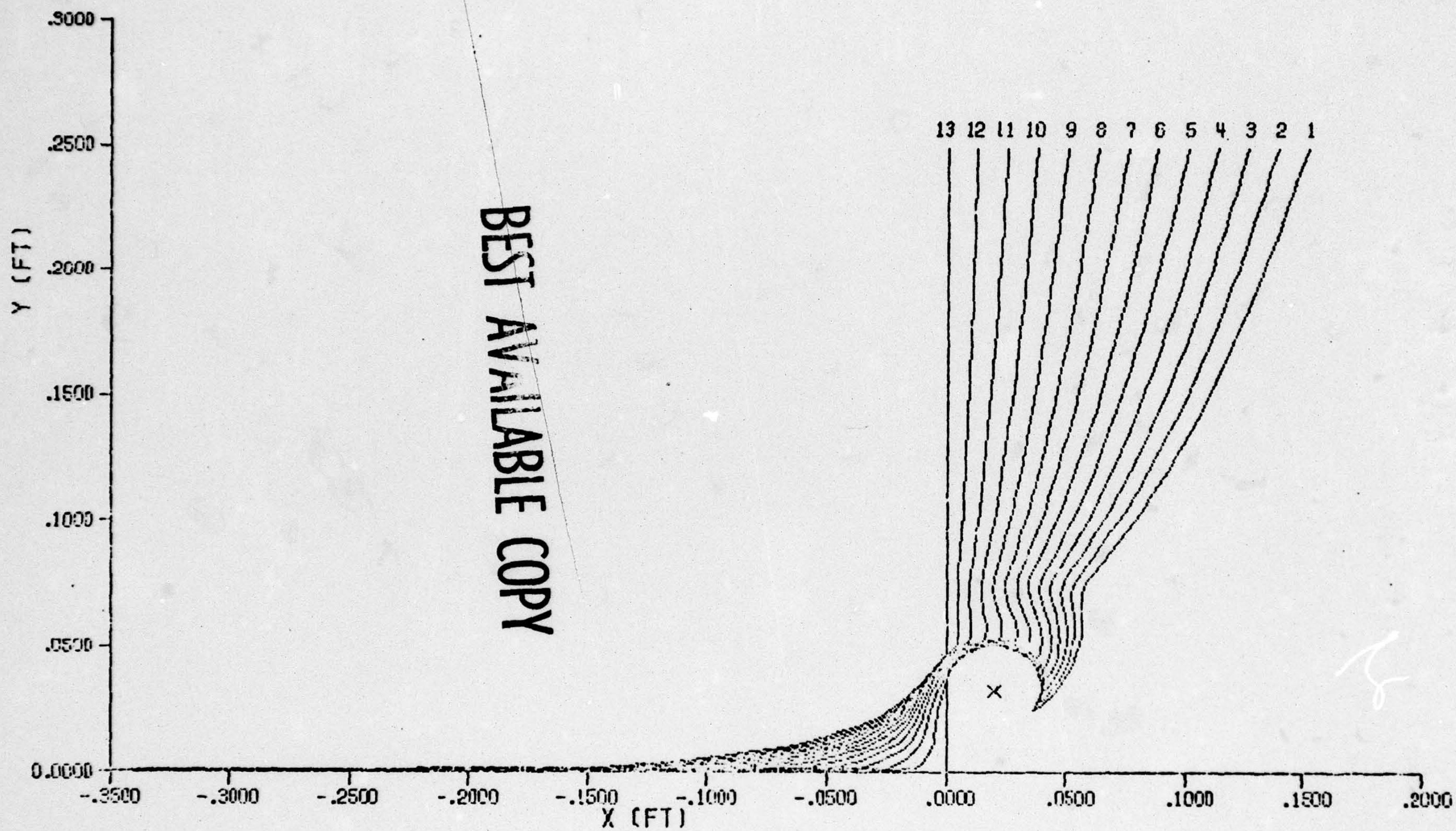




Figure 10. Hydrogen bubble wire simulation with wire moving at same speed as vortex but with the vortex center ahead of the wire.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is an interim annual report for an ongoing research program studying coherent structure in turbulent boundary layers. The design and development of a water channel facility for use in flow visualization studies of coherent turbulent boundary structure is described. The particularly unique aspects of this facility include the incorporation of 1) a moving reference (viewing) platform for study of relative motion effects and 2) a closed circuit television monitoring and recording system. Preliminary flow visualization results are presented for both a fixed and moving reference frame, and a tentative

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vortex-loop model of coherent turbulent boundary layer structure is proposed. Computer simulations of a transverse structure in a turbulent boundary layer are presented showing a remarkable similarity with experimental flow visualization results. Research directions for the following year are outlined.